Precision Top Quark Mass Measurements at CDF

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5. **Systematic Uncertainties**
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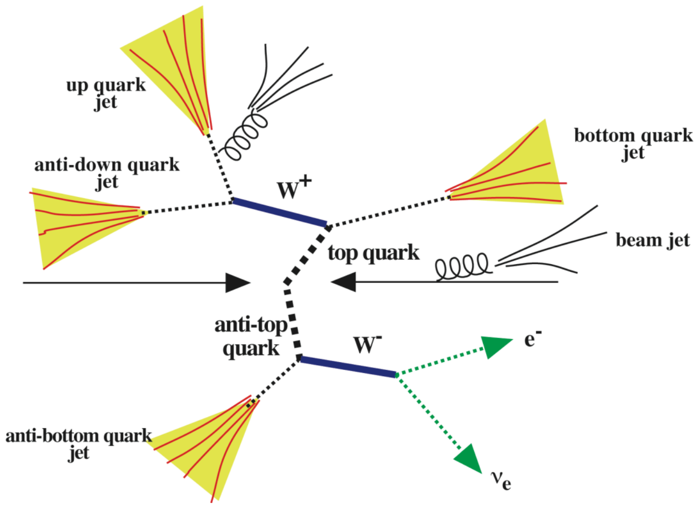
The Top Quark Mass

- **A precision measurement of top quark mass m_t scientifically important**
  - **Tests consistency of Standard Model**
  - **Bare quark – first opportunity to study one directly**
  - **Heaviest fermion, so couples strongly to Higgs boson**
- **Not just "another" quark mass**
  - **Heaviest fermion in theory**
    - Couples to Higgs boson in SM
    - m_Z, m_W, m_t and m_H are all related
  - **At a level of ~0.5 GeV/c^2, start to test other aspects of theory**
    - Stability of pole mass with respect to MS-bar mass
    - Non-perturbative QCD effects become important
- **In SUSY models,**
  - **Top coupling to lightest Higgs boson forces it to be below about 140 GeV/c^2**
  - **Precision measurement provides constraints on alternate models**
- **Presents important experimental challenges**
  - **Requires us to understand**
    - Jet energy scales very well
    - Effects of underlying event
- **Important as a calibration tool for other searches and measurements**
  - **E.g., Higgs decaying to jets**

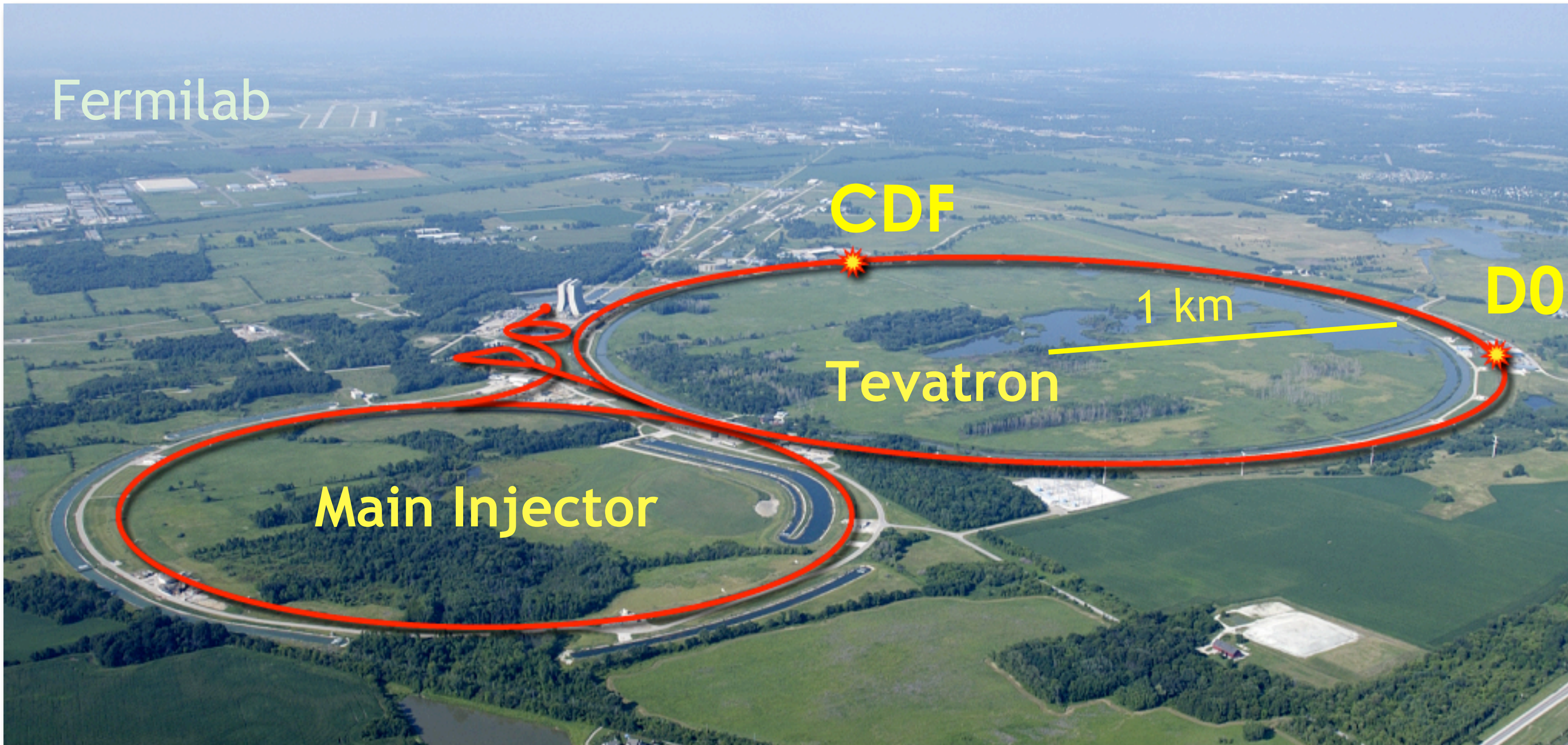
Measurement Strategy

- **Top quark expected to decay 100% into $W^{+}b$**
  - **Have all-hadronic and semileptonic decay modes**
  - **Pair production dominates**
    - End up with 6 parton final state
    - With additional jets



- **Identify the decay products of top quark pairs**
  - **Select events with**
    - Charged lepton + neutrino
    - 2 jets from 2nd W decay
    - 2 more jets from b quarks
  - **Employ energy-momentum conservation to infer m_t**
- **Measure every decay mode**
  - **Employ different techniques to test assumptions**
  - **Work to limit dependence on MC calculations**
  - **Constrain theoretical uncertainties**

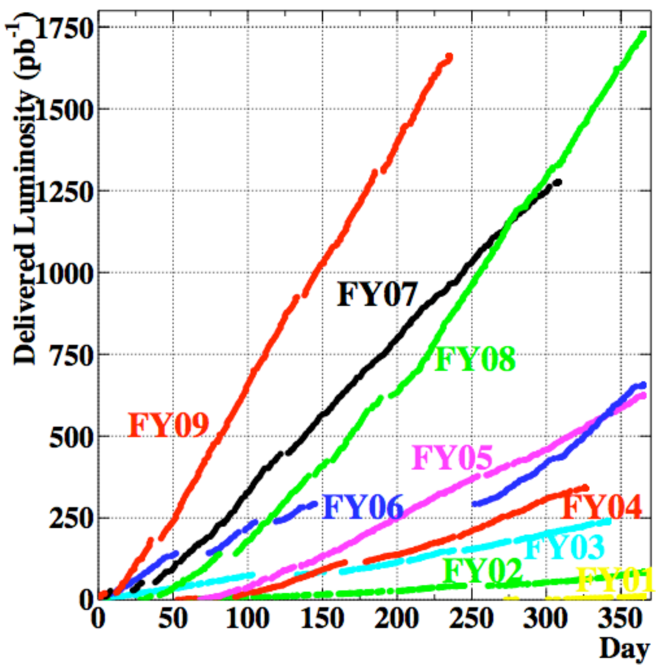
Fermilab Tevatron

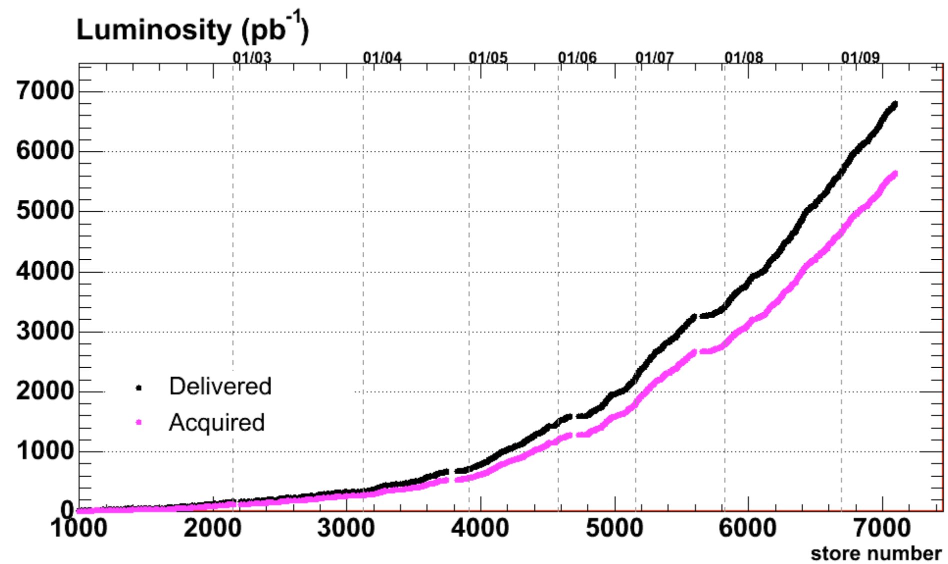


Tevatron Run II Performance

- Tevatron has run very well!
  - Initially a slow start in 2002-03
  - Exceeded goals over last three years
    - Record luminosity of $3.6 \times 10^{32}\ cm^{-2}s^{-1}$
  - Now accumulating ~2 fb^{-1}/year

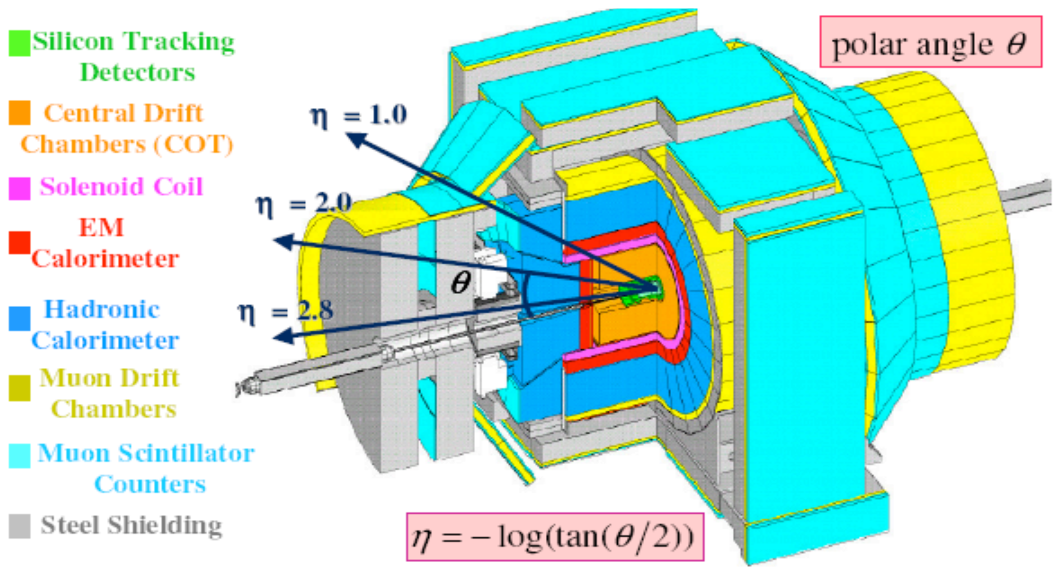
- This has led to a change in plans
  - Originally Tevatron was to shut down by Sep 2009
  - Now running through Sep 2010 is certain given recent budget decision
  - Discussions underway about running through Sep 2011





CDF Detector

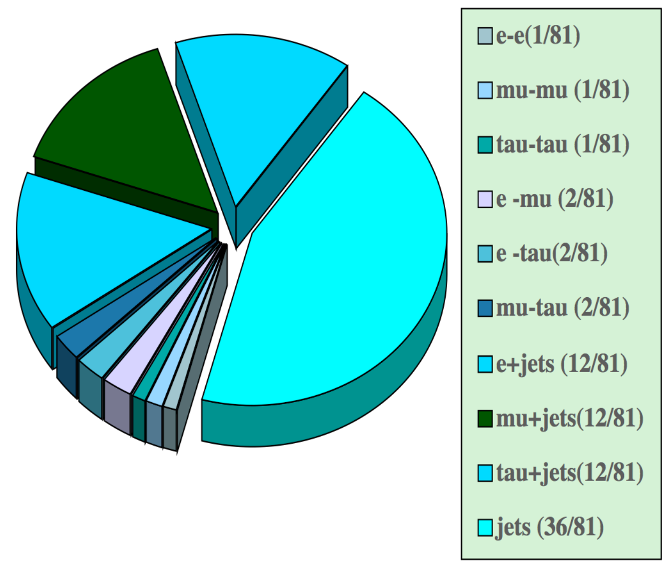
- **Collider Detector at Fermilab**
  - **Excellent charged particle tracking**
    - Large 1.4 T solenoid for particle momentum measurement
  - **Calorimeters measure jet energies and missing energy**
  - **Muon detectors outside of calorimeter**
- **Trigger & DAQ system designed to**
  - **Examine each beam crossing (2.4 MHz rate)**
  - **Select "interesting" events**
  - **Record data at rate of 100 Hz**



- **B tagging provided by 7-layer silicon tracking system**
  - **For top quarks, tagging efficiency is ~45%**
  - **Essential tool to reduce backgrounds in mass analyses**

Top Quark Reconstruction

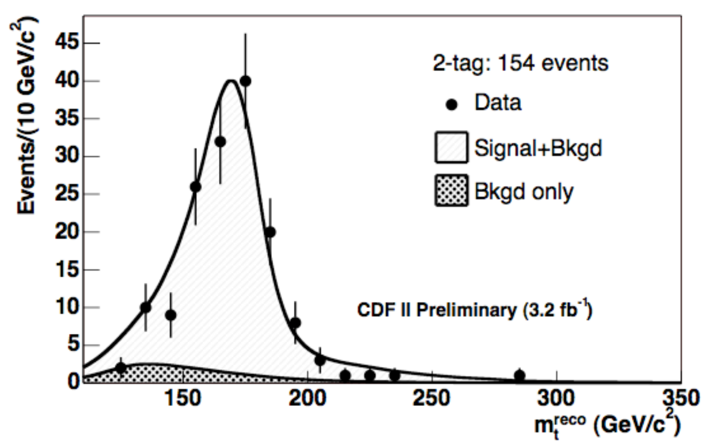
- **Goal is to efficiently identify each event topology**
  - **Dileptons (~4%)**
    - 2 leptons (e,μ) $P_T > 20$ GeV/c
    - Missing $E_T > 20$ GeV
    - 2 or more jets
      - **P_T>20 GeV/c and |η|<2**
  - **Lepton + jets (~30%)**
    - 1 lepton (e,μ) $P_T > 20$ GeV/c
    - Missing $E_T > 20$ GeV
    - 2 or more jets
      - **P_T>20 GeV/c and |η|<2**
  - **All Hadronic (~44%)**
    - 6 or more jets
      - **P_T>15 GeV/c and |η|<2**
    - Kinematic cuts + neural nets



- **Limited also by systematic uncertainties**
  - **Techniques and selection optimized to reduce systematics**
  - **Much innovation over last five years**
- **Using "3rd generation" techniques**

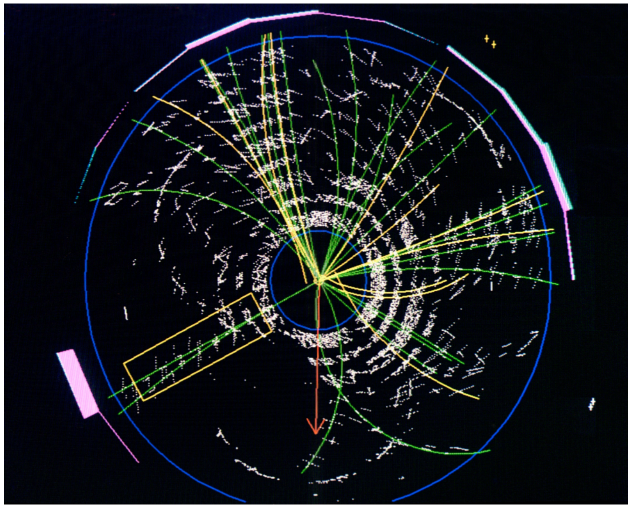
Mass Measurement Techniques

- **All techniques based on simple kinematics**
  - **Heavier the object, the more energetic the daughters**
- **Variations in how one correlates observed final state with m_t**
  - **Directly measure using 4-momentum reconstruction**
    - Correct for resolution effects
  - **Employ matrix element approach**
    - Use "transfer functions" for detector resolution
  - **Look at subset of information**
    - Example, lepton P_T
- **Many complications**
  - **Cannot reconstruct final state of 6 partons correctly**
  - **Jet energy calibrations**
  - **Background sources**
- **Example of how well one can do:**
  - **Mass reconstruction in double-tagged lepton+jet events**



More on Techniques

- **Have to understand effects of background**
  - **Purity of samples improved**
    - Using neural network techniques to estimate
  - **Data-driven with many cross checks**
  - **Latest measurements use**
    - Neural net techniques to improve S/B
    - Use event-by-event S/B estimates
- **Systematic uncertainties now play significant role**
  - **Jet energy scales have been largest experimental challenge**
  - **Theory now becoming single largest source**
- **Employing increasingly sophisticated tools to extract m_t**
  - **Neural nets for backgrounds**
  - **Likelihood approaches using**
    - Expected response functions (templates)
    - Matrix element approaches with transfer functions to model detector response
  - **Combined analyses**



Latest Results in Lepton+Jets

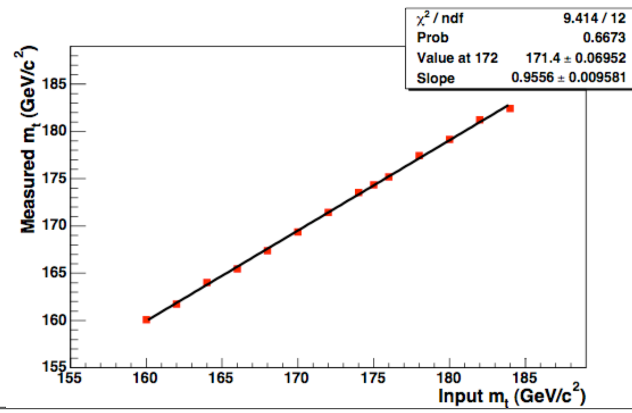
- **Current "best" measurement - MTM3**
  - **Standard event selection on 3.2 fb[-1] sample**
    - Observe 459 single tag events and 119 double tags
  - **Estimates background probability event-by-event**
    - Neural network using 10 observables
  - **Calculate likelihood using**
    - Matrix element for production & decay
    - Transfer functions to account for detector effects
    - Determine jet energy scale JES simultaneously
  - **Fit observed jet and lepton 3-vectors to m_t and JES**
    - Sum over all possible combinations of parton-jet assignments

Background	1 tag	$\geq$ 2 tags
non-W QCD	23.4 ± 20.4	1.6 ± 2.3
W+light mistag	22.1 ± 5.7	0.4 ± 0.2
diboson (WW, WZ, ZZ)	5.5 ± 0.6	0.5 ± 0.1
$Z \to ee, \mu\mu, \tau\tau$	3.6 ± 0.5	0.3 ± 0.1
Sum of above 3	31.2 ± 5.8	1.2 ± 0.2
$W + b\bar{b}$	32.4 ± 12.5	6.6 ± 2.2
$W + c\bar{c}$	19.4 ± 6.7	0.9 ± 0.3
$W + c$	10.3 ± 3.6	0.5 ± 0.2
Single top s-chan	2.4 ± 0.3	0.9 ± 0.1
Single top t-chan	2.7 ± 0.3	0.7 ± 0.1
Sum of above 5	67.2 ± 21.8	9.5 ± 2.6
Total background	121.8 ± 31.7	12.3 ± 4.4
Events observed	459	119

$$L(\vec{y} \mid m_t, \Delta_{\rm JES}) = \frac{1}{N(m_t)} \frac{1}{A(m_t, \Delta_{\rm JES})} \sum_{i=1}^{24} w_i L_i(\vec{y} \mid m_t, \Delta_{\rm JES})$$

with

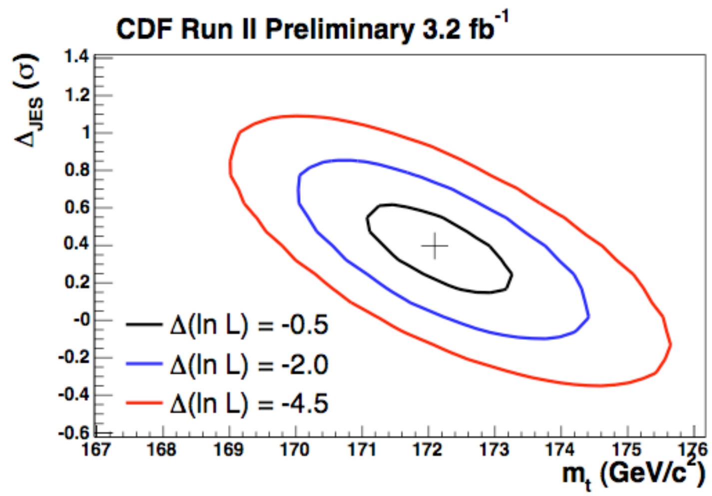
$$L_i(\vec{y} \mid m_t, \Delta_{\rm JES}) = \int \frac{f(z_1) f(z_2)}{FF} \, \mathrm{TF}(\vec{y} \mid \vec{x}, \Delta_{\rm JES}) \, |M(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$



MTM3 Results

- **Systematic effects**
  - **Four dominant contributions**
    - MC generator
      - **Compare PYTHIA with HERWIG**
    - Residual JES
      - **light quark to b quark**
    - Background effects
      - **Uncertainties from different sources**
    - Color reconnection
      - **Model using different "tunes" in PYTHIA**

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.2
MC generator	0.5
ISR and FSR	0.3
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.4
Total	1.1



CDF Collaboration, CDF Conf. Note 9692 (2009)

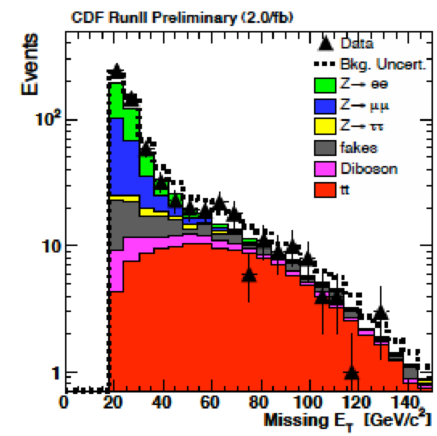
- **Overall result is:**

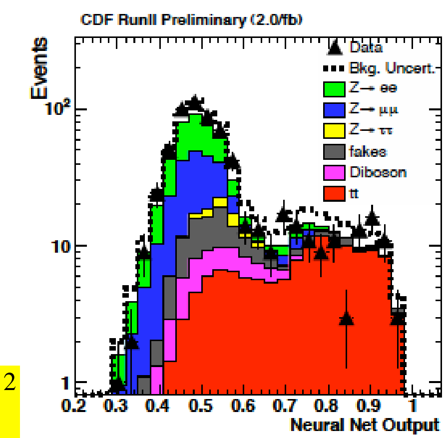
$$m_t = 172.1 \pm 0.9\,(\text{stat}) \pm 0.7\ (\text{JES}) \pm 1.1\ (\text{syst})\ \text{GeV/c}^2$$
$$= 172.1 \pm 1.6\ \text{GeV/c}^2$$

Top Quark Mass in Dileptons

- **Dilepton final states have complication of 2 neutrinos**
  - **Missing E_T is sum of neutrino P_T**
  - **Extract m_t using matrix element technique**
    - Integrate over neutrino momenta
- **Analyze 2.0 fb^{-1} of data**
  - **Employ neural network to reduce backgrounds**

N_{tags}	0	≥ 1
Z ee	56.3 ± 13.7	2.3 ± 1.1
Z $\mu\mu$	48.6 ± 12.0	1.7 ± 0.8
Z	11.6 ± 4.0	0.1 ± 0.1
Z $ee + bb$	1.8 ± 0.6	4.3 ± 2.2
Z $\mu\mu + bb$	1.5 ± 0.5	3.4 ± 1.8
Z $+ bb$	0.2 ± 0.1	0.2 ± 0.1
Z $ee + cc$	3.0 ± 0.9	1.2 ± 0.7
Z $\mu\mu + cc$	2.4 ± 0.7	1.0 ± 0.5
Z $+ cc$	0.4 ± 0.2	0.0
WW	11.0 ± 5.5	0.4 ± 0.4
WZ	3.3 ± 1.7	0.2 ± 0.2
ZZ	2.3 ± 1.1	0.1 ± 0.1
W	0.7 ± 0.2	0.0
$fakes$	29.0 ± 8.7	4.5 ± 1.1
tt	43.8 ± 4.4	78.0 ± 6.2
Total	215.8 ± 21.9	97.5 ± 7.2
Data (2.0 fb^{-1})	246	98





Source	Size (GeV/c^2)
Jet Energy Scale	2.5
Lepton Energy Scale	0.1
Generator	0.7
Method	0.4
Sample composition uncertainty	0.3
Background statistics	0.5
Background modeling	0.2
FSR modeling	0.3
ISR modeling	0.3
PDFs	0.6
Total	2.9

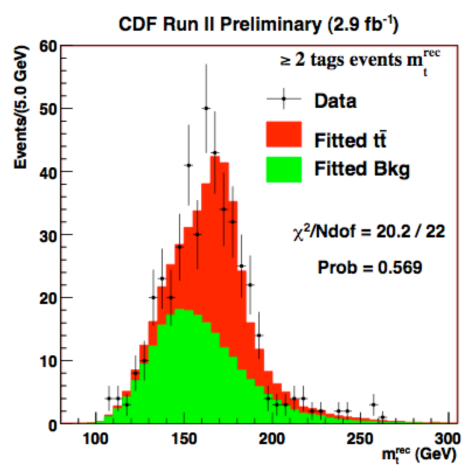
- **Measured mass:**

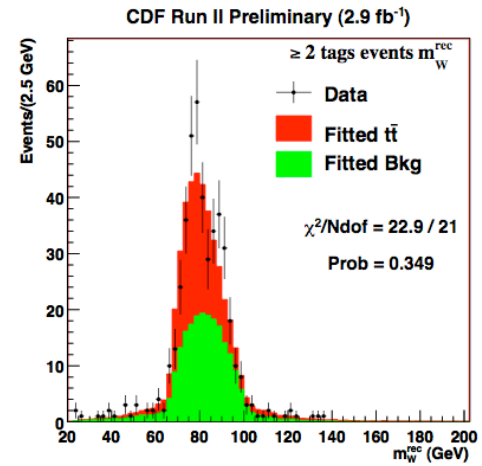
$$m_t = 171.2 \pm 2.7\,(\text{stat}) \pm 2.9\,(\text{syst})\ \text{GeV/c}^2$$
$$= 171.2 \pm 4.0\ \text{GeV/c}^2$$

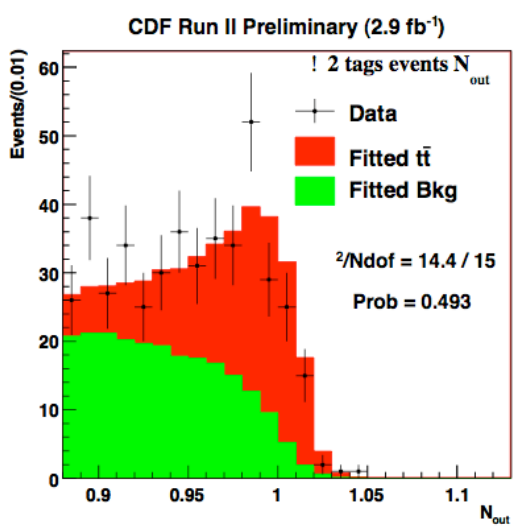
CDF Collaboration, Phys. Rev. D75, 031105 (2007)

Top Quark Mass in All Hadronic Mode

- **Challenges here are QCD + JES**
  - **S/B is about 10^{-3} after trigger**
  - **All-jet final state**
    - Jet energy scale calibration dominates
- **Strategy**
  - **Use kinematic cuts + b-tagging**
    - Require at least 2 tagged jets
  - **Neural network to reduce background (use 13 variables)**







Source	δM_{top}^{syst} (GeV/c^2)	$\delta\Delta\mathrm{JES}^{syst}$
Residual bias	$^{+0.8}_{-0.4}$	$^{+0.18}_{-0.24}$
2D calibration	$<$ 0.1	$<$ 0.01
Generator	0.3	0.25
ISR/FSR	0.1	0.06
b-jets energy scale	0.2	0.04
SF E_T dependence	0.1	0.01
Residual JES	0.5	– –
PDF	$^{+0.3}_{-0.2}$	$^{+0.05}_{-0.04}$
Multiple Hadron Interactions	0.2	0.01
Color Reconnections	0.4	0.08
Templates Statistics	0.3	0.07
Background Shape	0.1	0.02
Background Normalization	0.2	0.05
Total	$^{+1.2}_{-1.0}$	$^{+0.34}_{-0.37}$

- **Result is quite robust, given intrinsic S/B problems**
- **In 2.9 fb^{-1} of data, measure:**

$$m_t = 174.8 \pm 1.7\,(\mathrm{stat}) \pm 1.6\ (\mathrm{JES})\ {}^{+1.2}_{-1.0}\ (\mathrm{syst})\ \mathrm{GeV}/c^2$$

$$= 174.8 \pm 2.4\,(\mathrm{stat})^{+1.2}_{-1.0}\ (\mathrm{syst})\ \ \mathrm{GeV}/c^2$$

CDF Collaboration, CDF Conf. Note 9694, (2009)

Plus Many Other Analyses

- **Highlighted the most precise results in three channels**
  - **Many other analyses completed, e.g.**
    - Soft muon tagged l+jets
    - Combined template analysis in l+jets & dileptons
    - Lepton P_T distribution
    - Neutrino weighting technique with dileptons
    - Template technique in all-hadronic mode
    - L_{xy} and P_T of lepton
  - **Have different backgrounds & systematics**
  - **Reinforce confidence in overall results**

Input	Run II Preliminary				Run I Published		
	LJT	DIL	HAD	$L_{xy}+P_T^{lep}$	LJT	DIL	HAD
M_{top}	172.1	171.2	174.8	175.3	176.1	167.4	186.0
Statistical	0.9	2.7	1.7	6.2	5.1	10.3	10.0
iJES	0.7	0.0	1.6	0.0	-	-	-
aJES	-	-	-	-	-	-	-
bJES	0.4	0.4	0.2	0.0	0.6	0.5	0.6
cJES	0.3	1.7	0.5	0.0	2.7	2.6	3.0
dJES	0.1	0.1	0.1	0.0	0.7	0.6	0.3
rJES	0.4	1.9	0.2	0.1	3.4	2.8	4.0
Lepton P_T	0.2	0.1	-	1.1	-	-	-
Signal	0.3	0.8	0.2	1.6	2.6	2.8	1.8
Generator	0.5	0.9	0.3	0.6	0.1	0.6	0.8
UN/MI	-	-	-	-	-	-	-
Background	0.5	0.4	0.4	1.6	1.3	0.3	1.7
Method	0.2	0.6	0.7	1.4	0.0	0.7	0.6
Color Reconnections	0.4	0.4	0.4	0.4	-	-	-
Multiple Hadron Interactions	0.1	0.2	0.2	0.7	-	-	-
Statistical	0.9	2.7	1.7	6.2	5.1	10.3	10.0
Systematics-Total	1.3	3.0	1.9	3.1	5.3	4.9	5.7
Total	1.6	4.0	2.6	6.9	7.3	11.4	11.5

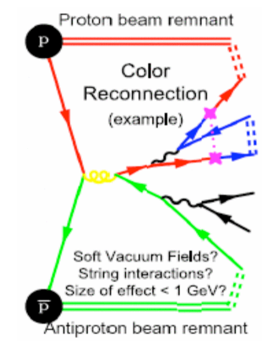
Combining Results

- Combined measurement
  - **Most channels statistically independent**
    - In a few cases, have to take into account overlap in data sets
  - **Requires analysis of systematic uncertainties**
    - Group into uncorrelated/correlated sources
- Significant work by D0 and CDF to ensure common definitions
  - **Similar to the efforts made at LEP**
  - **Resulted in joint publications of combined m_t and m_W measurements**

- Effects can be represented through a correlation matrix

	Run II Preliminary				Run I Published		
	LJ	DIL	HAD	$L_{xy}+P_T^{lep}$	LJT	DIL	HAD
LJT	1						
DIL	0.36	1					
HAD	0.17	0.19	1				
$L_{xy}+P_T^{lep}$	0.20	0.12	0.06	1			
LJT	0.35	0.46	0.15	0.17	1		
DIL	0.19	0.28	0.10	0.08	0.29	1	
HAD	0.21	0.33	0.13	0.07	0.32	0.19	1

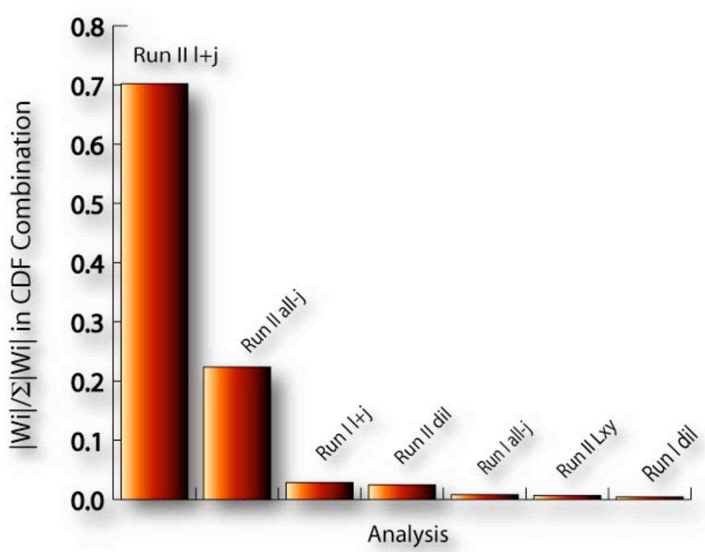
  - **Largest uncertainties in combined result arise from**
    - Jet energy scale (which is formally a statistical uncertainty in many cases)
      - **Light quark/b quark jet response**
    - Monte Carlo modelling
    - Theoretical uncertainties
      - **Color reconnection recent "new" effect**

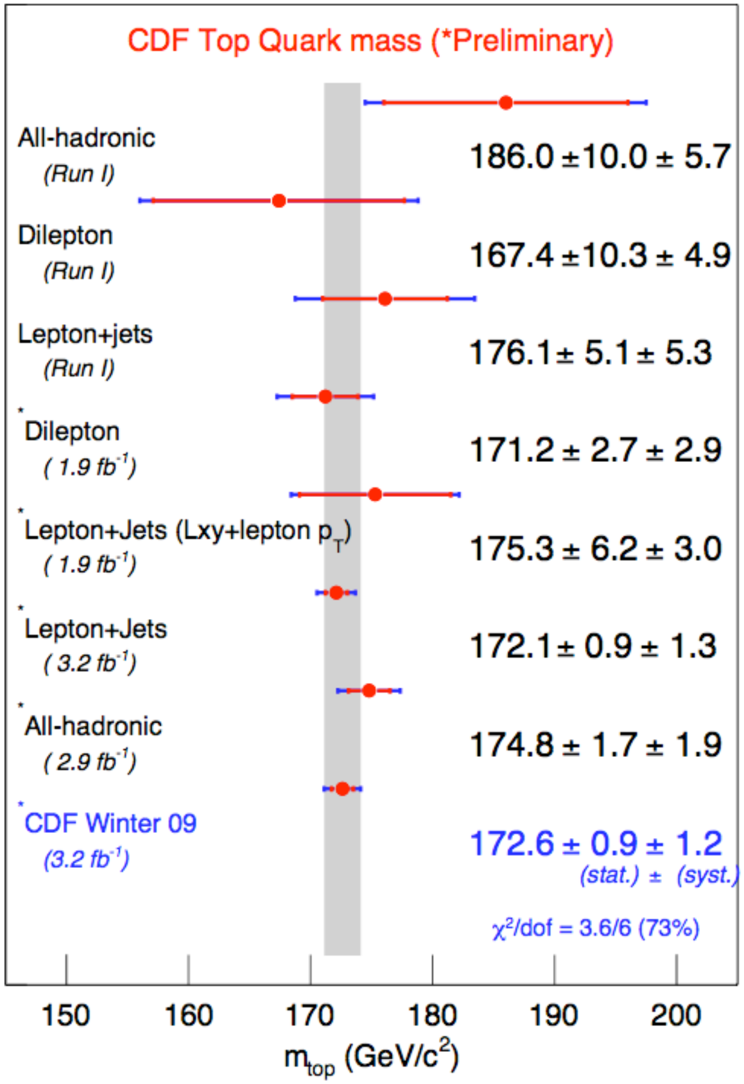


D. Wicke and P. Skands, arXiv:0807.3248V1

CDF Combined m_t Result

- **Have combined all CDF measurements from both Run I and Run II**
  - **Lepton+jets is single most-accurate result**
  - **However, others add substantially**
    - Increased statistical power
    - Different systematics (to a degree)
      - **These are now limiting factor in precision**

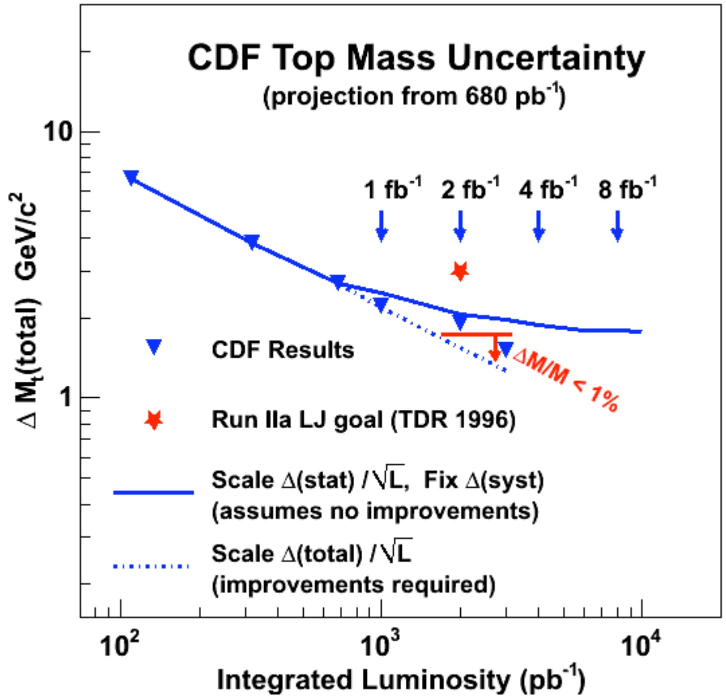




Summary

- **Top quark mass precisely measured**
  - **Uncertainty now exceed goals**
  - **Most precisely known quark mass**
    - Uncertainty ~ 0.9% or 1.5 GeV/c²

$$
\begin{aligned}
m_t &= 172.6 \pm 0.9\,(\text{stat}) \pm 1.2\ (\text{syst})\ \text{GeV/c}^2 \\
&= 172.6 \pm 1.5\ \text{GeV/c}^2
\end{aligned}
$$

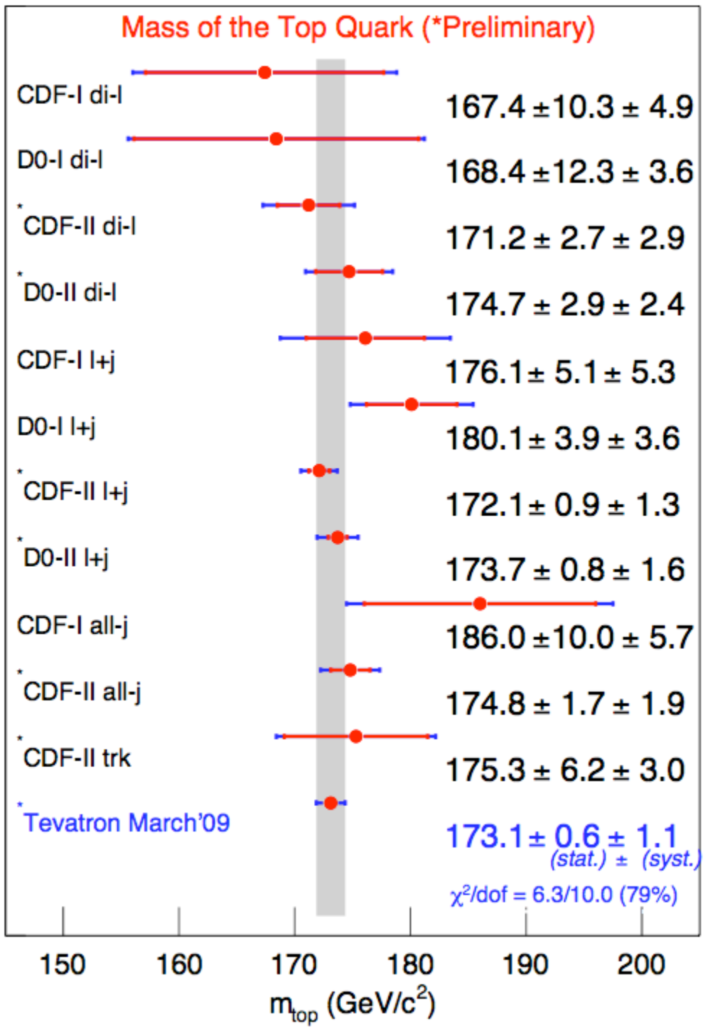


- **Expect uncertainties to improve with increasing luminosity**
  - **Already have x2 more data to analyze**
    - Expect to collect another 5 fb^{-1}
  - **Its power will depend on continued efforts to reduce systematic uncertainties**

Backup Slides

Combined Mass Results

- CDF and D0 combination most powerful single measurement
- Now are becoming systematics-limited
- Have to push on many fronts to improve
  - Theoretical modelling
  - Jet energy systematics



Combination Inputs

	Run I published					Run II preliminary					
	CDF			DØ		CDF				DØ	
	all-j	l+j	di-l	l+j	di-l	l+j	di-l	all-j	trk	l+j	di-l
$\int \mathcal{L}\, dt$	0.1	0.1	0.1	0.1	0.1	3.2	1.9	2.9	1.9	3.6	3.6
Result	186.00	176.10	167.40	180.10	168.40	172.14	171.15	174.80	175.30	173.75	174.66
iJES	0.00	0.00	0.00	0.00	0.00	0.74	0.00	1.64	0.00	0.47	0.00
aJES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	1.32
bJES	0.60	0.60	0.80	0.71	0.71	0.38	0.40	0.21	0.00	0.07	0.26
cJES	3.00	2.70	2.60	2.00	2.00	0.32	1.73	0.49	0.60	0.00	0.00
dJES	0.30	0.70	0.60	0.00	0.00	0.08	0.09	0.08	0.00	0.84	1.46
rJES	4.00	3.35	2.65	2.53	1.12	0.40	1.90	0.21	0.10	0.00	0.00
lepPt	0.00	0.00	0.00	0.00	0.00	0.18	0.10	0.00	1.10	0.18	0.32
Signal	1.80	2.60	2.80	1.11	1.80	0.34	0.78	0.23	1.60	0.45	0.65
MC	0.80	0.10	0.60	0.00	0.00	0.51	0.90	0.31	0.60	0.58	1.00
UN/MI	0.00	0.00	0.00	1.30	1.30	0.00	0.00	0.00	0.00	0.00	0.00
BG	1.70	1.30	0.30	1.00	1.10	0.50	0.38	0.35	1.60	0.08	0.08
Fit	0.60	0.00	0.70	0.58	1.14	0.16	0.60	0.67	1.40	0.21	0.51
CR	0.00	0.00	0.00	0.00	0.00	0.41	0.40	0.41	0.40	0.40	0.40
MHI	0.00	0.00	0.00	0.00	0.00	0.09	0.20	0.17	0.70	0.05	0.00
Syst.	5.71	5.28	4.85	3.89	3.63	1.35	2.98	1.99	3.11	1.60	2.43
Stat.	10.00	5.10	10.30	3.60	12.30	0.94	2.67	1.70	6.20	0.83	2.92
Total	11.51	7.34	11.39	5.30	12.83	1.64	4.00	2.61	6.94	1.80	3.80

Implications for SM Higgs

- **Including all electroweak observables**
  - **W boson mass measurements**
    - LEP 2 and Tevatron
    - $80.399 \pm 0.025\ \mathrm{GeV/c^2}$
  - **Constrain the Higgs boson mass**
    - Formal 95% CL limit
      - **$M_H < 163\ \mathrm{GeV/c^2}$**